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DRAG TESTS
OF THE
BRITISH SQUID

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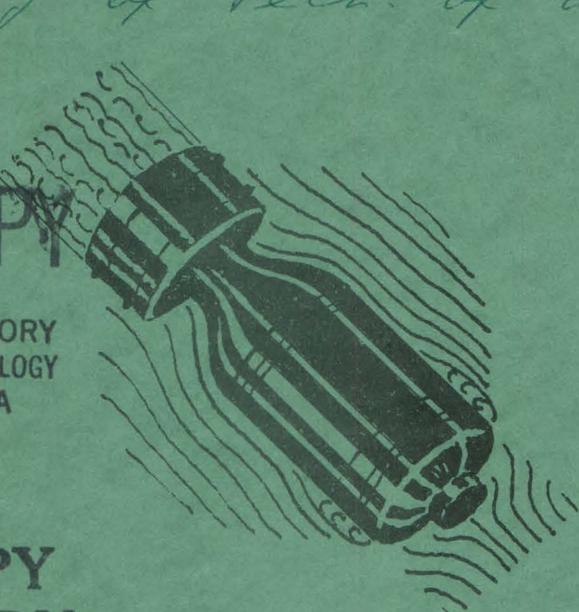

THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY.
PASADENA, CALIFORNIA

SECTION № 6.1-sr 207 1904
HML № ND-24.2

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DRAG TESTS
OF THE
BRITISH SQUID

ROBERT T. KNAPP
OFFICIAL INVESTIGATOR

THE HIGH SPEED WATER TUNNEL
AT THE
CALIFORNIA INSTITUTE OF TECHNOLOGY
HYDRAULIC MACHINERY LABORATORY
PASADENA, CALIFORNIA

Section No. 6.1-sr207-1904

HML No. ND-24.2

Report Prepared by

Gerald B. Robison
Hydraulic Engineer

January 8, 1945

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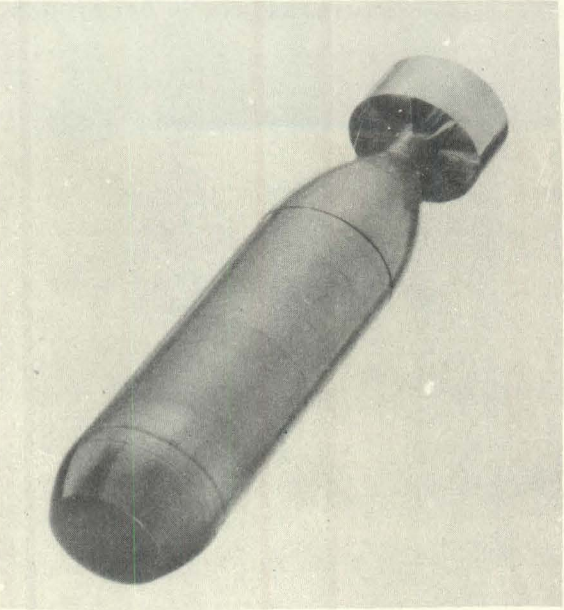

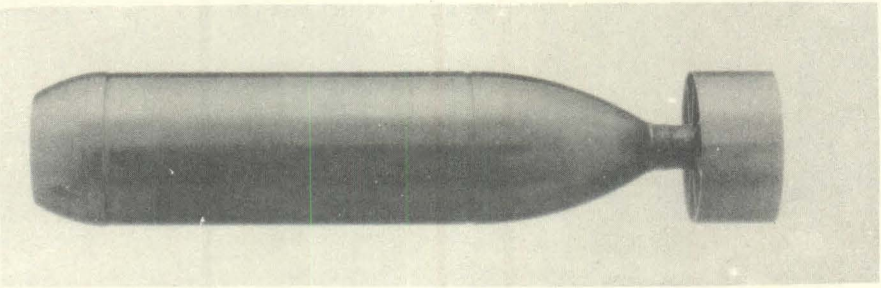

FIGURE 1

Production Model of British Squid Projectile Type "C"

California Institute of Technology New Nose, New Tail

DRAG TESTS

OF THE

BRITISH SQUID, PROJECTILE TYPE "C"

REFERENCES

All references pertain to the British Squid, Type "C" Projectile.

1. Report Section No. 6.1-sr207-933, October 29, 1943: "Water Tunnel Tests of the British Squid Projectile Type 'C'." This initial test was to determine performance characteristics and cavitation effects with varying water pressures.

2. Report Section No. 6.1-sr207-938, November 29 1943: "Water Tunnel Tests of the British Squid Projectile Type 'C' with Two Alternate Flat Noses." This second test dealt with the effect of three different noses which were similar except for the diameter of the flat face which was, variously, 7.90", 8.93", and 9.95".

3. Memorandum Report M-24, December 8, 1944: "Drag Measurements on the British Type 'C' Projectile." This Report was made as a result of marked differences in British and California Institute of Technology tests of the Squid. These were found to be due, in major part, to extra thick fins and shroud ring on the original California Institute of Technology model tail. Results are discussed below.

4. Memorandum Report M-24.1, December 11, 1944: "British Type 'C' Projectile at High K Values." This report covered tests of the current production model at high pressures. Results are included herein.

See Appendix for formulae used.

AUTHORIZATION

Authorization for this test is contained in a letter of January 17, 1944 from Dr. E. H. Colpitts, Chief of Section 6.1, Office of Scientific Research and Development.

PURPOSE OF THIS REPORT

The purpose of this report is to correlate the subject matter of Memorandum Reports M-24 and M-24.1. The purpose of the Memorandum Report M-24, December 8, 1944, was to obtain the drag coefficients for the model with a correctly proportioned tail. The purpose of Memorandum Report M-24.1, December 11, 1944, was to determine the drag coefficients of a true model of the current production type, with a new nose, at high K values, that is, at high pressures.

SUMMARY OF RESULTS

Considerable differences in California Institute of Technology and British tests of the British Squid Projectile, Type "C", were shown to have been caused, in major part, by a CIT model tail which was not in strict scale. The remaining difference is of an order which can be attributed to lack of complete similarity in streamlining and structure of the models.

Tests of a model of the current production type with a nose bourrelet gave nearly identical drag coefficient values to those mentioned immediately above. This drag coefficient was found to remain practically constant, at about 0.20 for a Reynolds number of 1.25×10^6 for values of K, the cavitation parameter, up to 18. This is equivalent to a depth of 533 feet below sea level for a terminal velocity of 45 feet per second. Extrapolated values of the drag coefficient predict a terminal velocity of 45 feet per second in sea water of 54° F.

SUMMARY OF PROTOTYPE DATA

Overall length 55 inches = 4.583 feet

Maximum diameter = 11.9 inches used in calculation of

$$A_D = \left[\frac{11.9}{12}\right]^2 \times \frac{\pi}{4} = 0.772 \text{ square feet}$$

Weight of projectile in air = 386.4 pounds

Weight of projectile in salt water = 234 pounds

These weights were taken from Drawing No. L.S. 203.

DESCRIPTION OF MODEL CHANGES

The original model, used in the 1943 tests, was made to 1 : 5.95 scale (approximately 1 : 6) in all parts except the metal thickness in the ring and fins of the tail. An arbitrary minimum thickness of 1/32" was adopted for the model on the erroneous assumption that the true scale thickness would be too light to withstand handling and testing. The variations in thickness, from correct ratio values, were :

Model ring thickness	0.031"
True scale ring thickness	0.015"
Model fin thickness	0.031"
True scale fin thickness	0.011"

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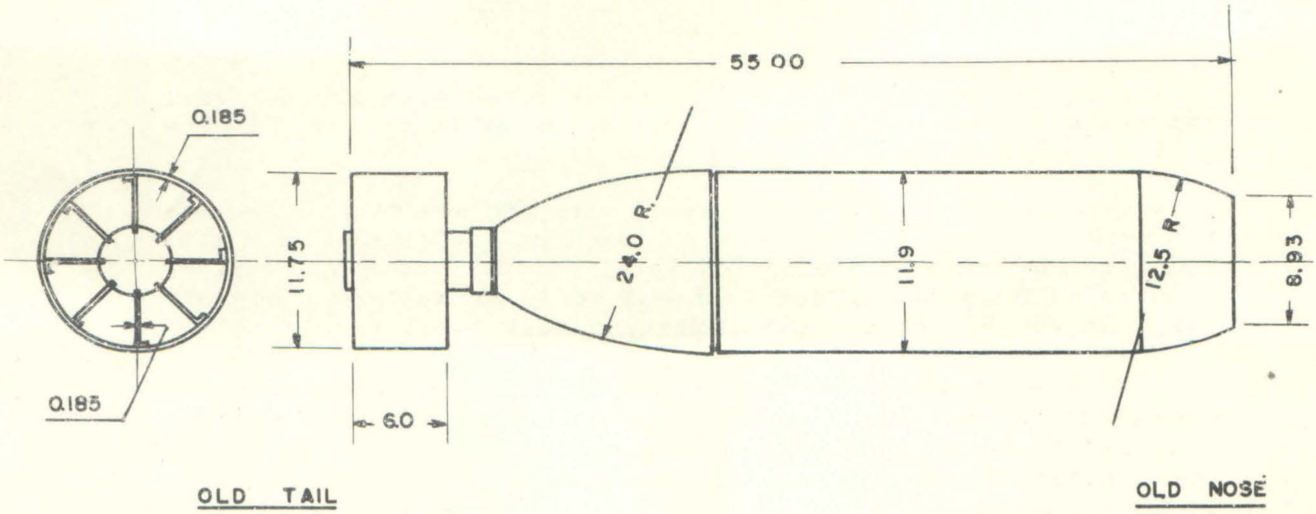

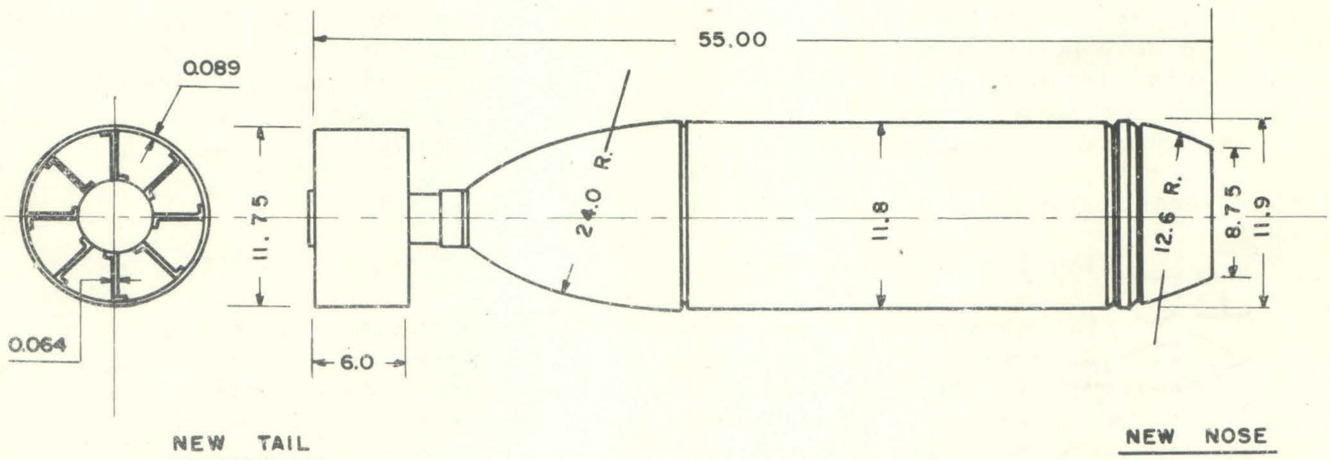

PRODUCTION MODEL OF BRITISH SQUID PROJECTILE
TYPE C

FIGURE 2

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A new model of the tail was constructed with correct tail thickness and tested. This tail is referred to as the "CIT New Tail".

Shortly subsequent to the tests with the new tail, a request was received for a determination of the drag coefficient of a true model of the current production form, without gas ring, corresponding to deep depths for K from 3 to 30 or such part of that range as was obtainable with existing test facilities.

Five production models at Morris Dam were inspected and measured. It was apparent that some changes had been made as compared to drawings previously supplied. The principal change was a reduction of 0.1 inch in body diameter, but with the previous maximum diameter (11.9) left as a bourrelet at the junction of nose and body. A casting of the outline of a selected average nose was made in plaster of Paris and reproduced to model scale. The drag coefficients were calculated on the basis of the projectile area at the maximum nose diameter.

Figure 1 shows the model with new nose and new tail. Figure 2 shows drawings of what are referred to, herein, as old and new noses; old and new tails. The bourrelet is clearly visible. The groove behind the nose is a reproduction of the weld joining the nose and body of the prototype. The appearance of the old nose may be seen in the flow diagrams, Figure 9. Differences in new and old tails cannot be observed in the photographs.

PERFORMANCE

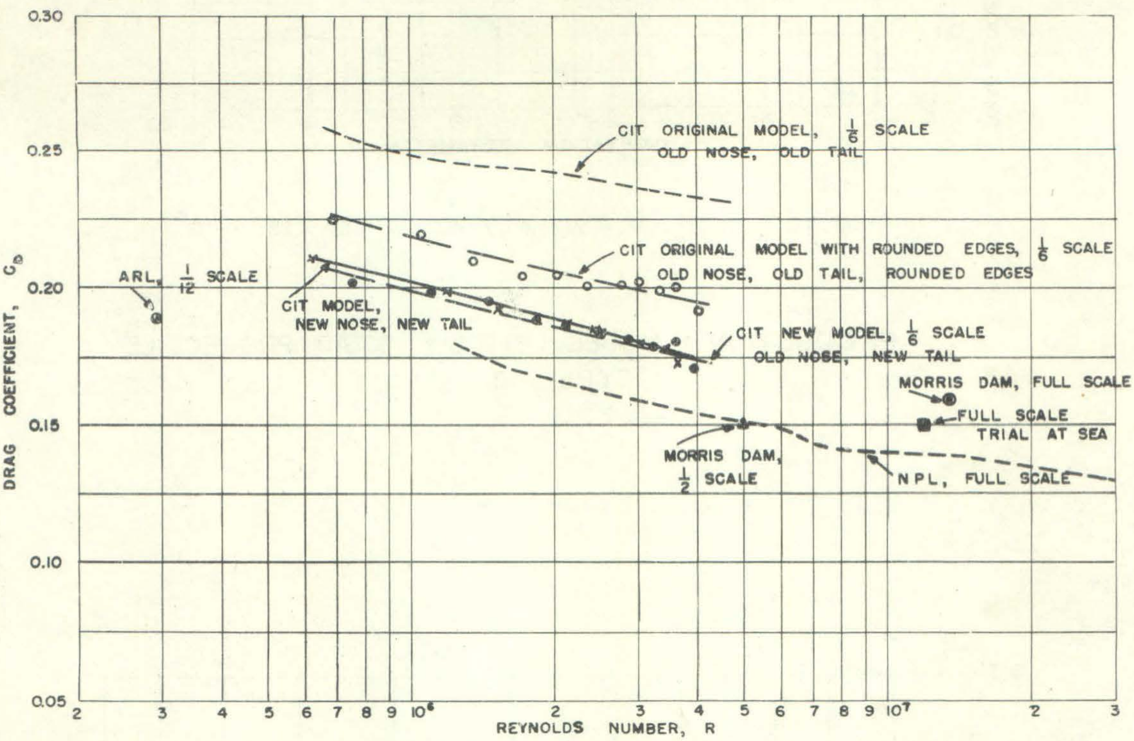
With the New Tail, Old Nose:

Drag measurements were made in the Water Tunnel for various Reynolds numbers. The reduction obtained in the drag suggested an investigation of the effect of rounding the leading edges of the thick fins and ring of the original model tail. This was done and tests were made. Results are shown in Figure 3.

With the New Tail, New Nose:

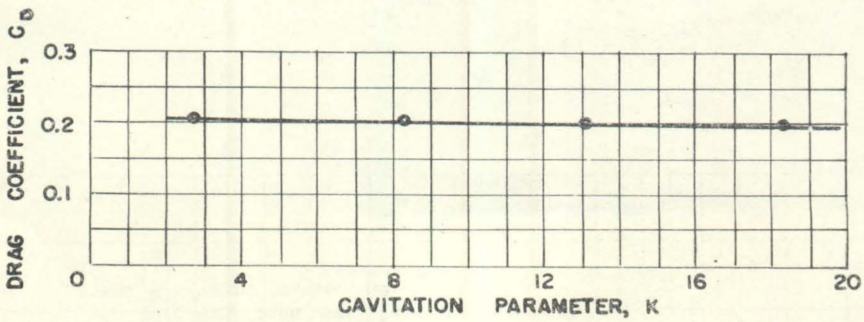
Tests were made in the Water Tunnel over the maximum range of pressure obtainable and with a constant velocity of approximately 20 ft/sec. This gave C_D points for a K range of 3 to 18. Results are shown in Figure 4.

An additional run was made at a constant pressure of approximately 20 lbs/sq inch gage over the velocity range obtainable in order to provide data for the new nose shape, which could be compared with many previous measurements of C_D vs Reynolds number. Results obtained are shown in Figure 5.



BRITISH SQUID PROJECTILE
TYPE C

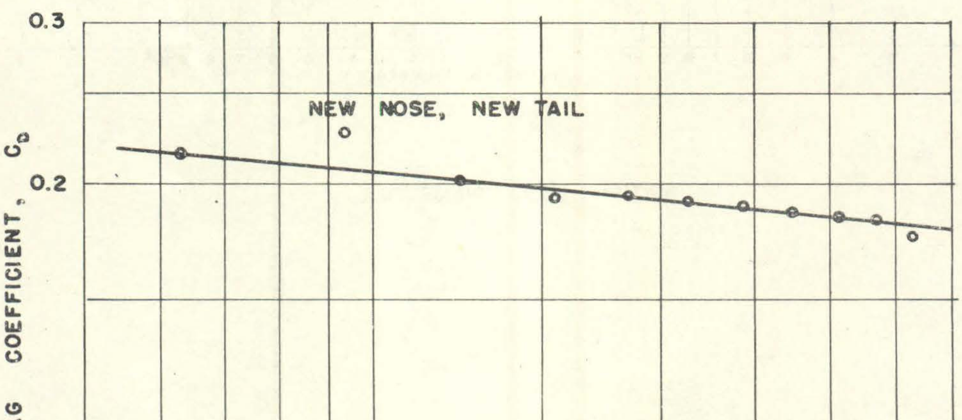
FIGURE 3



$\psi = 0°$ V = 20 FT / SEC R = 1.25×10^6

PRODUCTION MODEL BRITISH SQUID PROJECTILE
TYPE C

FIGURE 4



PRODUCTION MODEL BRITISH SQUID PROJECTILE
TYPE C

FIGURE 5

DISCUSSION

New Tail, Old Nose

An inspection of the curves of Figure 3 shows that the California Institute of Technology tests with the new tail gave results which are within about 9% of those of the National Physical Laboratory tests. This is probably as good an agreement as could be expected.

The reduction in the drag coefficient due to the thinner metal in the fins and ring can be calculated as follows: The excess frontal area of the thick fins and ring is 0.216 square inches, which is 7% of the frontal area of the full diameter of the model. If it is assumed that the drag coefficient for a plate moving normal to its surface is 1.0, then the increase in drag coefficient for the projectile, on account of the 7% increase in frontal area of the fins and ring, will be 1.0 x 0.07 or 0.07. It is seen from the curve that this is in fair agreement with observed results, as the increase in C_D at $R = 7 \times 10^5$ was 0.05 and, at $R = 4 \times 10^6$, it was 0.06.

It may be seen from the curve for the old tail model with thick fins rounded on the leading edges that this slight streamlining reduced the drag coefficient 12% to 16%. It is, however, still about 10% greater than for the new tail. There may have been some similar streamlining or other structural differences in the model used for the National Physical Laboratory tests. If so, this could easily account for the remaining difference between the California Institute of Technology tests and the National Physical Laboratory results.

The decrease in C_D due to rounding the edges of fins and ring is 0.0375 (taken from the curves of Figure 3). The frontal area of the thick fins and ring is 0.383 square inches or 12.5% of the frontal area of the full diameter of the model. The C_D for the rounded fins and ring is found to be $\frac{0.0375}{0.125} = 0.3$, of that assumed for the plate, which is a reasonable value.

On the curve sheet, Figure 3, is shown one point which is a Morris Dam determination of the drag of a full-scale model, taken from Report No. CIT-1OC-28, June 20, 1944. This test showed the drag coefficient to be 0.16 at a Reynolds number of approximately 1.3×10^7, which seems in fair agreement with the California Institute of Technology tests on the 1/6 scale model. Data pertaining to Admiralty Research Laboratory, National Physical Laboratory, and full-scale trial at sea were taken from the chart sent with a letter from Mr. R. C. Hopgood dated July 24, 1944.

New Tail, New Nose

Figure 4 shows the drag coefficient, C_D, plotted against K, the cavitation parameter, for the production model. No significant changes were noted from a value of C_D = 0.20 at Reynolds number 1.25 x 10^6 within the range of K, or simulated submergence, obtainable in the Water Tunnel. The value of C_D = 0.20 given herein is the value 0.21 given in Memorandum Report of December 11, 1944, corrected for the tunnel pressure gradient.

The highest measured K value was 18. If we anticipate terminal velocities in the range 43 to 45 ft/sec, the sea depths at which K would be 18 for these velocities for this particular projectile can be calculated from the formula:

$$\text{Depth (in feet below sea water level)} = \frac{Kv^2}{2g} - 33.2$$

Using K = 18, g = 32.2, and v = 43, 44, and 45, successively, we get

V, ft/sec	Equivalent depth below sea level, feet
43	484
44	509
45	533

Since the formula for fresh water is

$$\text{Depth} = \frac{Kv^2}{2g} - 34.0$$

the difference, for the same assumed velocities, is negligible, being less than one foot smaller.

The plot of drag coefficient, C_D, against K, the cavitation parameter is, in effect, the relationship of the drag coefficient to changes in pressure for some assumed constant velocity. Minute changes in the value of ρ due to changes in the value of g or changes in salinity with increased depth seem to be negligible. So also is the effect of change in kinematic viscosity with lower water temperatures. There is no evidence that, for a given constant velocity, the drag coefficient would change at still higher pressures or greater depths. The possible change of drag coefficient at such greater depths, if the velocity is not absolutely constant for a definite period, is another matter. Before discussing that condition, it is desirable to give other data.

The first, faint, permanent cavitation for the production model was observed at K = 2.03. This corresponds closely with the nearest comparable nose, the No. 45, which gave 2.06. The No. 45 nose is the "old nose" as shown in Figure 1.

Since $C_D = \frac{D}{1/2\ \rho\ V^2 A_D}$ and, at terminal velocity, D becomes equal to the underwater weight of the projectile (here taken for sea water as 234 pounds), we may substitute this value, together with A_D = 0.772 and $\frac{1}{2}\rho$ = 0.994 (for sea water) and obtain

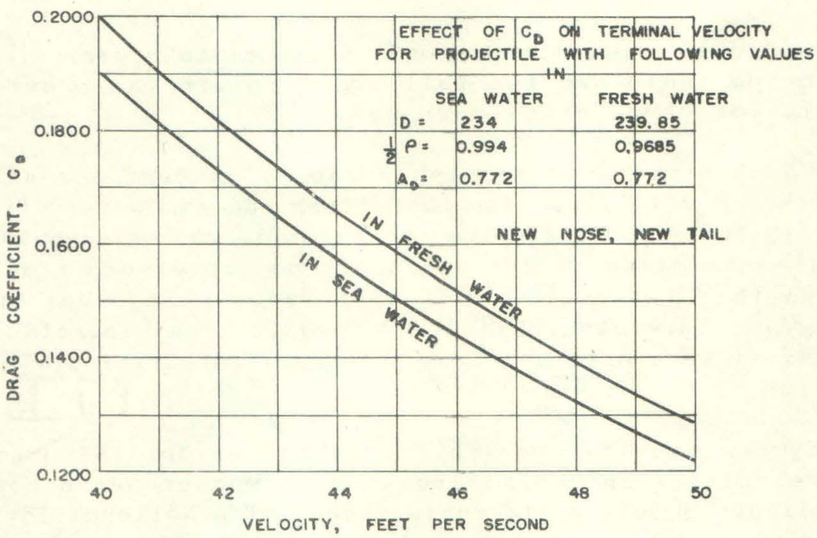
$$C_D = \frac{304.937}{V^2} \text{ for this projectile in sea water}$$

For fresh water, D will be 234 x 1.025 = 239.85 pounds;

$\frac{\rho}{2}$ will be 0.9685 and

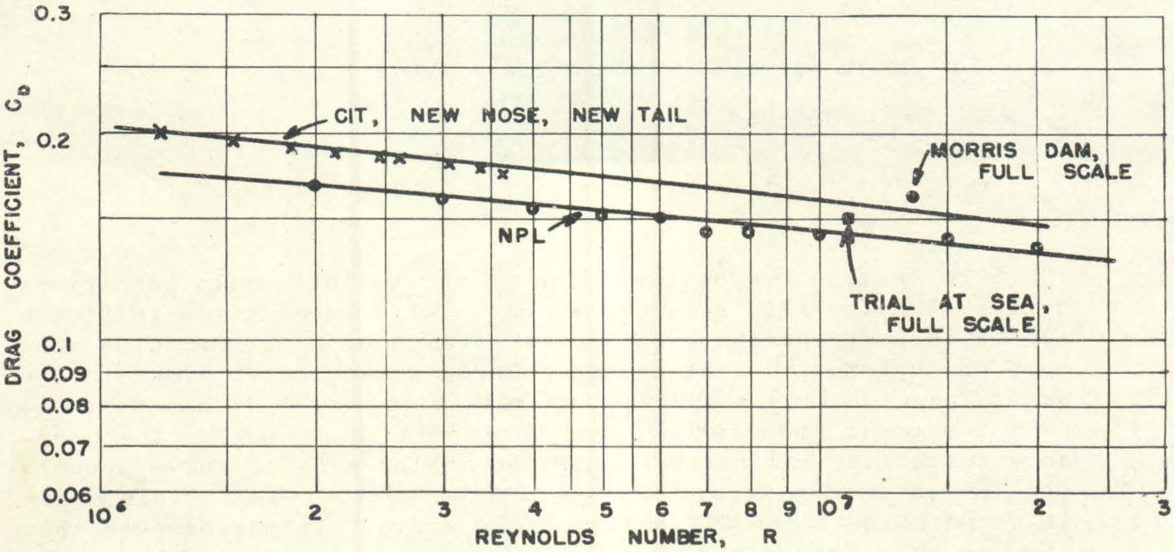
$$C_D = \frac{320.791}{V^2} \text{ for this projectile in fresh water.}$$

The terminal velocities, for C_D in the full-scale conditions anticipated for this projectile, only, will be as given in Figure 6. It is next necessary to know the value of C_D at Reynolds numbers encountered in service use. These cannot be obtained in the Water Tunnel. Figure 4 gives the result of tunnel tests, corrected for support interference and horizontal buoyancy. (The buoyancy correction had not been applied to the similar curve appearing in Memorandum Report M-24.1, December 11, 1944). This makes it comparable to the CIT curves of Figure 3. It may be seen that the new nose form gives practically the same values. This curve is definite only over the range R = 630,000 to R = 3,650,000. If this line, which is straight within limits of experimental accuracy over the observed range, be extended to R = 15,000,000, the indicated C_D is 0.15 as shown in Figure 7. This predicted value would give a terminal velocity in sea water of 45/ft./sec or 46.25 in fresh water (from Figure 6).



PRODUCTION MODEL BRITISH SQUID PROJECTILE
TYPE C

FIGURE 6



PRODUCTION MODEL BRITISH SQUID PROJECTILE
TYPE C

FIGURE 7

Figure 7 also shows the National Physical Laboratory results plotted to log scale and two full-scale points (as previously described), for comparative purposes.

Figure 8, with lines showing Reynolds numbers for various temperatures and velocities for both fresh and sea water, forms a chart upon which is indicated how the terminal velocity would vary with water temperature if our extrapolated curve held true. It may be seen that the velocity of 45 ft/sec would occur in sea water of temperature about 54° F. Values for the kinematic viscosity of water were obtained from International Critical Tables, First Edition.

We may now consider possible reasons for obtaining higher terminal velocities than anticipated from measurements not minutely duplicating full-scale performance. The National Physical Laboratory curve of C_D extends to service Reynolds numbers and shows certain departures from straight line relationship (when plotted on full logarithmic paper).

For a given projectile length and water temperature, l and V may be taken as constant and the Reynolds number will be directly proportional to the velocity - V.

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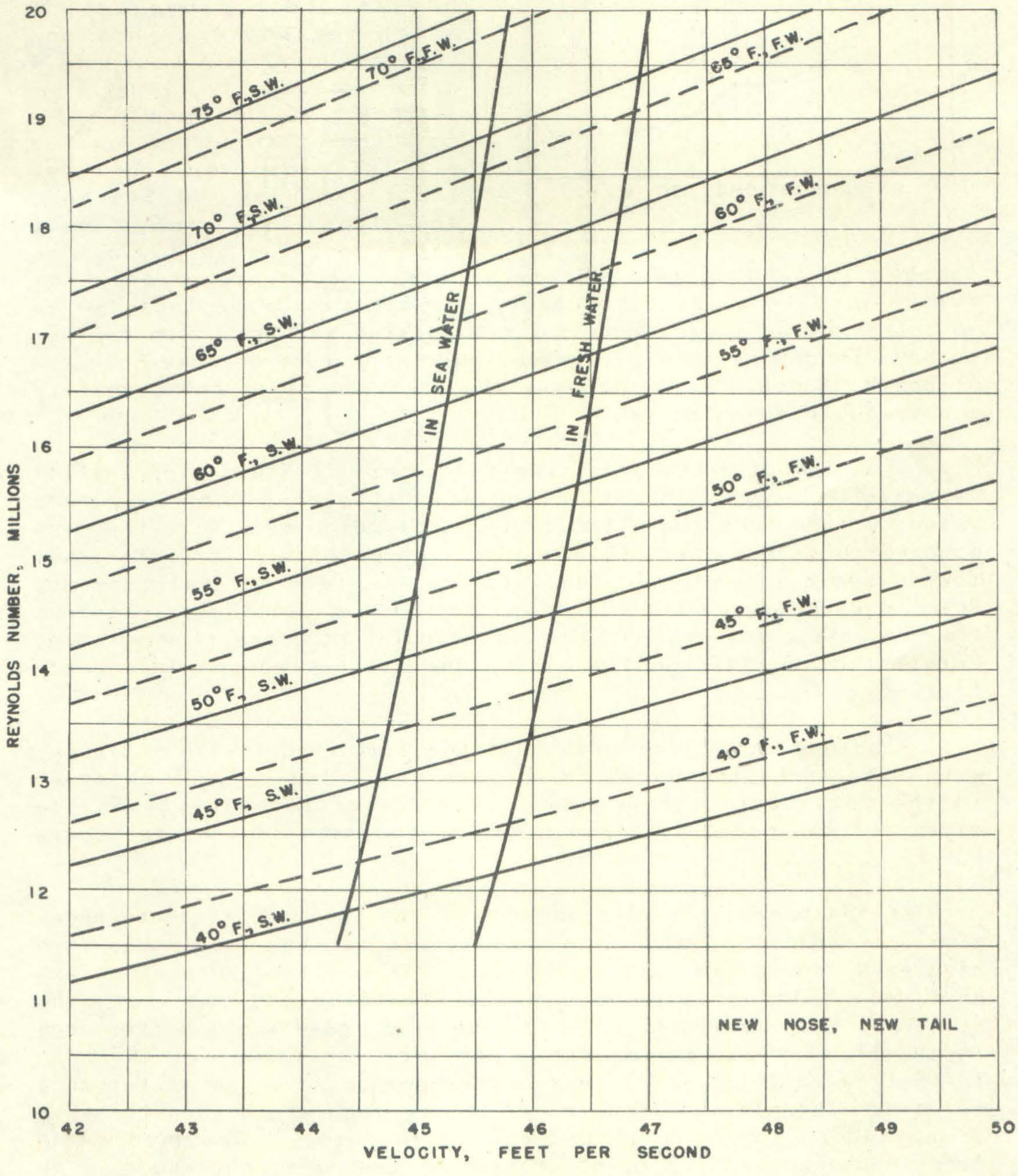

PRODUCTION MODEL BRITISH SQUID PROJECTILE
TYPE C

PREDICTED VELOCITIES FOR
SERVICE REYNOLDS NUMBERS

FIGURE 8

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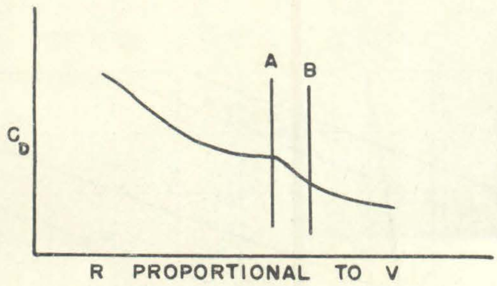

If we magnify the change in C_D, as indicated, it may be seen that a projectile which reached its terminal velocity at R = A would fall disproportionally slower than if at R = B. This would indicate the existance of one (or possibly more) critical velocities which, if reached, would result in a relatively rapid decrease in C_D, due to changes in flow pattern, thereby permitting a higher terminal velocity. It may be added that, for a period, the increase in velocity may be so moderate for the sinking projectile as to <u>seem</u> to have reached a terminal value, but there must be some acceleration which would carry it over the critical point and result in a noticeable speeding up.

When the projectile strikes the water, it has a high initial velocity. Impact and cavitation slow it almost certainly to a velocity less than the ultimate terminal velocity. With the disappearance of the air bubble and cavitation effect, gravitational forces begin to increase the velocity. A terminal velocity may seem to be achieved but, if there be still a small acceleration, the projectile may reach the critical point of a new flow pattern, permitting an additional velocity due to the reduced drag coefficient.

Figure 9 shows photographs of the Squid model with old nose, with flow lines indicated for angles of 0° and 12°, as observed in the Polarized Light Flume. Drawings of the flow lines are given for the model with new nose, at the same angles, in Figure 10.

It has previously been shown that the drag coefficients under similar conditions and initial cavitation for the models shown in Figures 9 and 10 are nearly the same. It would be natural to expect very little difference in the flow diagrams and it may be seen that they are small. The greatest of these small differences is in the flow pattern on the upper edge (as shown) of the nose in the yaw position. The bourrelet seems to move the disturbance forward. The maximum turbulence in both figures is seen to be in front and to the rear of the tail structure. The portion in front could be reduced by alteration of the afterbody shape. The extreme rear turbulence is caused by the blunt end.

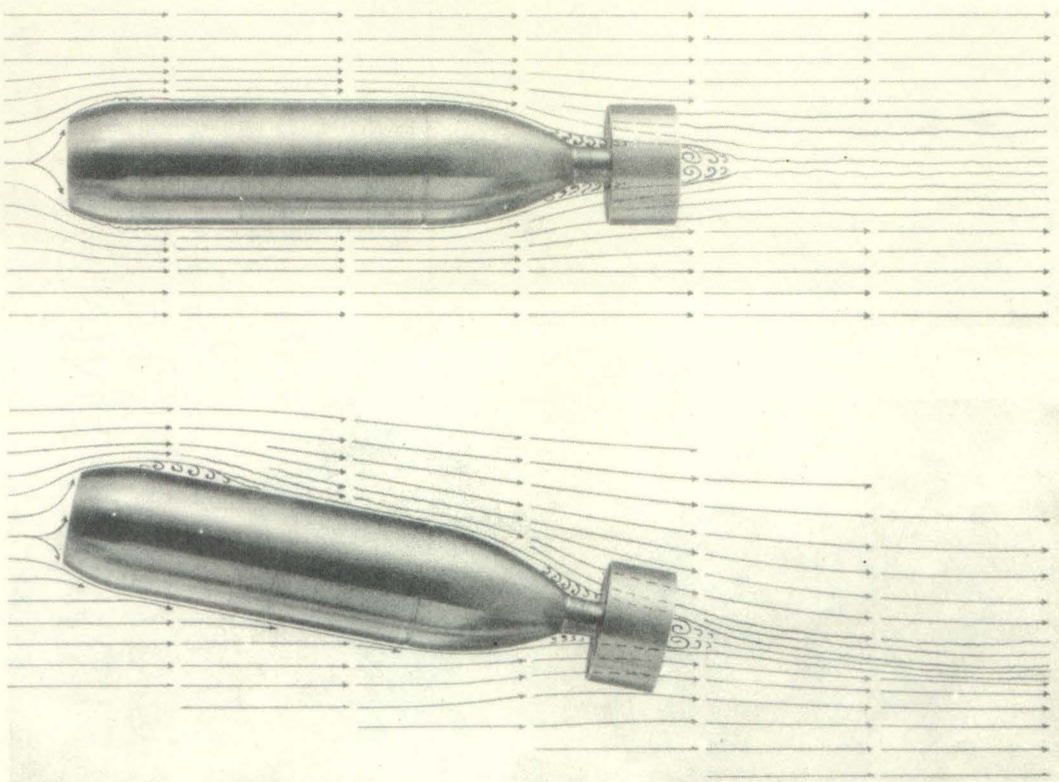

FIGURE 9

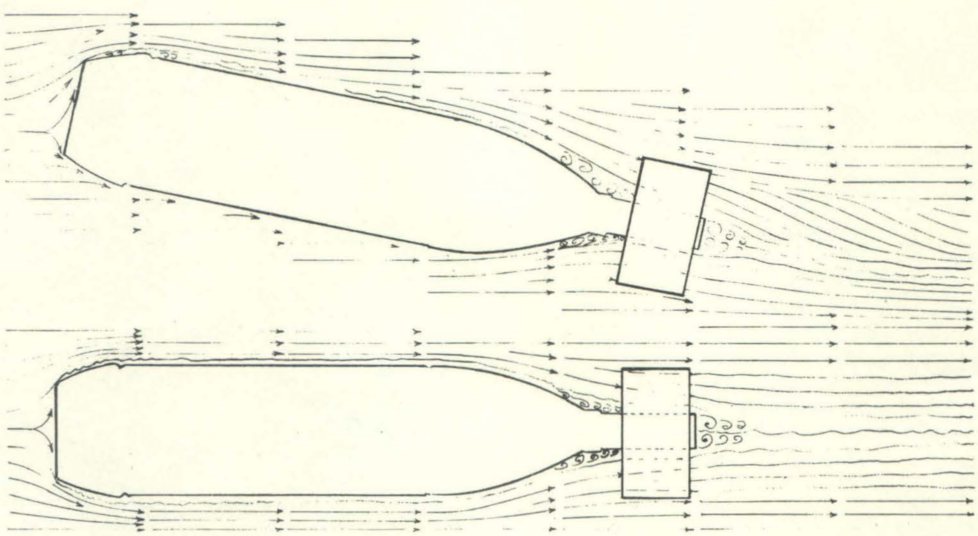

FIGURE 10

APPENDIX

Formulae used in this report

Drag Coefficient, $C_D = \dfrac{D}{1/2\ \rho\ V^2\ A_D}$

in which

D = measured drag force in pounds

ρ = density of fluid in slugs per cubic foot

V = mean relative velocity between the water and the projectile, in feet per second

A_D = area in square feet of a cross section of the cylindrical portion having the greatest diameter and taken normal to the longitudinal axis

Cavitation Parameter, K

$$K = \frac{P - P_V}{1/2\ \rho\ V^2}$$

in which

P = absolute static pressure in pounds per square foot

P_V = vapor pressure, at the corresponding water temperature, in pounds per square foot

ρ and V are as defined above

Reynolds Number, R

$$R = \frac{Vl}{\nu}$$

in which

V = velocity of projectile in feet per second

l = length of projectile in feet

ν = kinematic viscosity of water in square feet per second

Terminal Velocity

At terminal velocity in water, the drag becomes equal to the force exerted by the weight of the body in water

$$V^2 = \frac{D}{1/2\ \rho\ C_D\ A_D}$$

where

D = weight of body in air, in pounds minus buoyancy of body, in pounds

in which all other terms are as previously defined

Submergence in Sea Water

$$\text{Depth} = \frac{K\ V^2}{64.4} - 33.2$$

in which the depth is in feet below sea level and other terms are as previously defined